AD-A263 069

(7)

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS: None

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release: distribution unlimited.

DTIC ELECTE APR 2 1 1993 S B D

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION: Columbia University Electrical Engineering Dept.

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION: Office of Naval Research

6c. ADDRESS (City, State, and ZIP Code): 500 West 120th St. New York, NY 10027

7b. ADDRESS (City, State, and ZIP Code): 800 N. Quincy St. Arlington, VA 22217-5000

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: ONR

8b. OFFICE SYMBOL (If applicable): Code 1114

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Contract N00014-90-J-1536 R&T No. 414s006

8c. ADDRESS (City, State, and ZIP Code): Dr. Max N. Yoder, Office of Naval Research, Code 1114, 800 N. Quincy St., Arlington, VA 22217-5000

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification): Pseudomorphic Narrow Gap Materials for High Performance Devices

12. PERSONAL AUTHOR(S): Wen I. Wang, Professor

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM 12/15/89 TO 12/14/92	January 14, 1993	13

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

InAs field effect transistors (1 μm gate length) have been fabricated and showed extrinsic (intrinsic) transconductance as high as 414 mS/mm (670mS/mm). The cut-off frequency is shown to be more than a factor of two greater than is typical for GaAs based FET's with comparable gate length. Kink-free AlInAs/GaInAs/InP HEMTs have been fabricated. Heterojunction transistors with impact ionization at the emitter-base junction (i.e. when conduction band offset is larger than the band gap of the base) have been analyzed theoretically, and are shown to yield improved performance. Non-radiative Auger recombination in quantum wells has been analyzed in the context of strained lasers. We have also shown theoretically that infrared absorption at normal incidence due to intervalence subband transition can be greatly enhanced in light-hole and heavy-hole inverted strained GaInAs/AlInAs quantum wells.

93-08391

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Professor Wen I. Wang

22b. TELEPHONE (Include Area Code): 212 854-1748/3265

22c. OFFICE SYMBOL: MSL

OFFICE OF NAVAL RESEARCH

TECHNICAL REPORT

FOR

15 December 1989 through 14 December 1992

****

CONTRACT: N00014-90-J-1536

R&T NO: 414 s 006

TITLE OF CONTRACT: Pseudomorphic Narrow Gap Materials for High Performance Devices

NAMES OF PRINCIPAL INVESTIGATORS: Wen I. Wang, Professor

NAME OF ORGANIZATION: Electrical Engineering Department, Columbia University

ADDRESS OF ORGANIZATION: Electrical Engineering Department, Columbia University, 500 West 120th Street, New York, N.Y. 10027

****

The research performed during this reporting period started on December 15, 1989 and ended on December 14, 1992. The emphasis of our research under this program is to obtain high quality pseudomorphic (strained) narrow gap materials for high performance device applications. During the past three years, many strained-layer electronic and optical devices have been conceived and developed. The achievements are summarized in the following report:

High Breakdown Voltage InAs Channel Field-Effect Transistors

In InAs, the high electron mobility allows carriers to gain velocity quickly, while the large satellite valley spacing should yield higher carrier transient and steady-state velocities than both InP and GaAs. As a result, both long and short channel InAs channel FET's should outperform InP and GaAs based devices. However, because of the narrow bandgap of InAs (0.36 eV) it has been predicted that breakdown due to impact ionization will severely limit device performance. In bulk InAs, it has been predicted that the threshold for breakdown due to impact ionization should be on the order of 6 kV/cm. To date these results have been supported by the fact that all InAs channel FET's have exhibited behavior indicative of breakdown at drain-to-source voltages near 1 V. In this paper we demonstrated the room temperature operation of an AlSbAs/InAs heterostructure FET (HFET) that operates at channel electric fields (20 kV/cm) several times higher than the predicted threshold for impact ionization. Maximum drain current densities of 450 mA/mm were measured and operation at a drain voltage (V_{ds}) as high as 2.2 V was observed without any indication of channel breakdown. In addition, transconductances as high as 414 mS/mm and output conductances as low as 33 mS/mm are also observed at room temperature, yielding voltages gains on the order of 10. Based upon a calculated source resistance (0.94 W-mm), the intrinsic transconductance was determined to be 670 mS/mm. From this transconductance, the cut-off frequency of the device can be estimated to be 39 GHz which is more than a factor of two greater than is typical for GaAs based FET's of comparable gate length (16 GHz). Also, since carrier velocities are not expected to saturate in InAs, a constant-mobility model is used to project cut-off frequencies in the 600 GHz range for 0.25 µm gate InAs FET's.

In addtion, several mechanisms for the breakdown enhancement have been proposed by us. In general these mechanisms depend on the different vertical and horizontal structure of the FET as compared to a bulk InAs sample. Nonetheless, whatever the reason, our results do demonstrate that bulk breakdown values do not define the limit for operation of InAs channel FET's, establishing that InAs FET's may operate at higher supply voltages than previously considered possible.

Kink-Free AlInAs/GaInAs/InP HEMTs

Lattice matched AlInAs/GaInAs/InP high electron mobility transistors (HEMTs) have demonstrated excellent DC and microwave performance. However, a peak in the DC output conductance plot, known as the "kink" effect, makes these structures undesirable for low noise and digital applications. We have successfully fabricated kink-free AlInAs/GaInAs/InP HEMT's which were grown under normal MBE growth conditions. Our results were attributed to the high quality AlInAs buffer layer that had been fine-tuned to closely match the lattice constant of the InP substrates.

The AlInAs buffer layer was grown with V:III flux ratio of 10. A very low lattice mismatch between the AlInAs buffer layer and the InP substrate of less than 3×10^{-4}, measured by a four crystal x-ray diffractometer, was achieved. Hall measurments show electron mobilities of 7500 cm^2/Vs at room temperature and 30,000 cm^2/Vs at 77K. The $1 \mu m$ gate-length devices fabricated with this structure exhibited a maximum extrinsic transconductance of 450 mS/mm and a maximum current density of 600 mA/mm. These results represent the best reported for this material system and device size to date. The drain I-V characteristics show no kink within the range of V_{GS} varying from 0.4V to -1.2V and V_{DS} varying from 0V to 2V. The DC output conductance exhibited no kink effect with V_{GS} varying from 0.3V to 0.9V and V_{DS} varying from 0V to 2V. The output conductance at the peak transconductance was found to be 35 mS/mm. The elimination of the kink effect can be attributed to our high quality AlInAs buffer layer and the excellent lattice matching, both of which were achieved under normal MBE growth conditions.

Analytic Theory of Heterojunction Transistors with Impact Ionization at the Emitter-Base junction (i.e, when conduction band offset is larger than the band gap of the base)

We investigated the potential and possibility of an Auger transistor (heterojunction transistors with impact ionization at the emitter-base junction when the conduction band offset is larger than the band gap of the base) by deriving an analytic theory, and then applied this analytic theory to investigate the performance of such a transistor in plausible material systems. We have included the effect of parasitics in this simple theory to project the figures of merit for high frequency applications. We investigated the single electron-hole pair generation dominated limit using material parameterization, and compared it with behavior of the same device in the absence of Auger generation.

The Auger transistor is a heterojunction bipolar transistor that utilizes impact ionization caused by injected hot carriers to generate electron-hole pairs. The Auger generation processes are similar to the impact ionization processes of the p-n junction except that the excess kinetic energy occurs through the potential step of injection instead of drift in an electric fields as in the p-n junction impact ionization. The Auger transistor is unique among hot carrier devices in that it does not need a large mean free path for successful operation. It also does not need the very short basewidth required in hot carrier unipolar transistors. Auger processes also become stronger with a decrease of the bandgap and increase cf the injected hot carrier energy.

The analysis suggests that Auger transistors, employing very small bandgap semiconductors in the heavily doped base and operating at low temperatures, will exhibit appealing performance as devices are scaled in size and operating voltage. We found that the net base resistance is reduced because of the impact ionization process contributes a negative differential resistance. Excess holes are collected at the base ohmic contact, producing a base current which flows out of the device terminal, opposite to the usual npn base current. Due to this reduced base resistance, a substantial increase in f_{max} of 45% is possible compared to a conventional HBT counterpart. Consequently, we concluded that the device is a suitable candidate for microwave power generation at high frequencies.

Modeling of Split-Gate and Dual-Gate InAs FETs

The superior electron transport properties of InAs and its staggered band alignment with AlGaSb can lead to FETs with an order of magnitude higher transconductance compared to existing devices based on the AlGaAs/GaAs material system. Split-gate and dual-gate FET structures offer performance advantages over a conventional single gate design, including increased transconductance. The larger transconductance is due in part to the high drift velocity in InAs which can be more fully exploited using a split-gate design. To quantify the benefits of the split-gate device, modeling calculations were performed comparing a dual-gate design to a single gate design. The results, shown in Figure 4, show that the maximum transconductance is achieved at a much smaller gate voltage swing compared to the single gate device. This smaller required gate voltage swing is advantageous for the InAs device since higher output currents can be obtained for lower voltage swings. The resulting reduced gate to source and drain to source voltages will aid

in minimizing the gate-leakage current and impact ionization of carriers that can occur in the narrow band-gap InAs channel.

The advantages of a dual-gate device are the increased function and greater gain that the second gate provides. This enhanced gain is especially important for InAs devices which so far have exhibited a relatively large output conductance. In AlGaAs/GaAs the trade-off is a faster roll-off of the gain with frequency in a dual-gate design than with the single gate design. Due to the lack of negative differential mobility in the velocity-field curves of InAs, this trade-off does not exist. Therefore, the electrons will maintain their velocity after passing through the first gate. The frequency response then, should more closely resemble that of a single gate device. Using a small signal model to analyze the dual-gate device, we showed that the transconductance of the dual-gate device will be almost that of a single gate devices. It was also shown that the output resistance of the dual-gate FET is much greater than a single gate device. Therefore the output gain of the dual-gate device is greater than that of the single gate device. Furthermore, we predicted the gain of the dual-gate device to be greater than the single gate device at low frequencies. We also predicted the overall gain of the dual-gate AlGaSb/InAs HFET could be up to 40 db greater than that for similar AlGaAs/GaAs devices

Non-radiative Auger Recombination in Quantum Wells

A major factor limiting the performance of long-wavelength semiconductor lasers is carrier loss due to Auger recombination. Band to band Auger recombination in InGaAsP and InGaSb bulk and quantum well structures are dominated by the CHHS process where an electron (C) recombines with a heavy hole (H) and excites a heavy hole (H) to a split-off band (S). In a strained quantum well, the in-plane heavy hole effective mass is reduced due to heavy and light hole band mixing. This reduction has been shown to reduce the threshold current and effectively increase the modulation speed in strained quantum well lasers.

We investigated the effect of the heavy hole effective mass on the Auger recombination process and derived an analytic expression for the in-plane heavy and light hole masses in a strained quantum well. We showed for the first time that the dominant CHHS Auger recombination process in InGaSb/AlGaSb strained quantum well structures can be suppressed because of the small in-plane heavy hole effective masses.

Consequently, low threshold and good temperature performance can be achieved in strained quantum well lasers. Calculations show that this suppression can occur both in InGaSb/AlGaSb and InGaAsP/InP strained quantum well structures. We concluded therefore that for laser structures operating in the infrared region, a strained structure will perform better than a lattice-matched structure.

Enhanced Exciton Absorption and Saturation Limit in Strained InGaAs/InP Quantum Wells

The discovery of the room temperature Stark shift of the exciton-absorption peaks in quantum wells (QW's) has made possible novel devices, such as MQW self-electro-optical effect devices (SEED's) and electro-optic modulators. SEED's have since become the key devices used in optical switching and optical computing. MQW modulators, which overcome the deficiencies associated with directly modulated semiconductor lasers, are excellent candidates for use in high speed communication transmitters.

In order to improve device performance, extensive research has been focused on increasing the exciton-absorption peak value and the saturation limit. We propose a new approach to raising these parameters, using MQW's in which the well layer is under tensile strain.

When tensile strain is applied to the QW, the effective mass of the top valence band can increase and change sign (corresponding to a change in the in-plane valence band structure). As the valence band effective mass is increased the effective mass of a direct exciton, formed by an electron from the conduction band coupling to a hole from the top valence band, can be drastically increased. An increase in exciton mass leads to a reduction of exciton radius (greater overlap of electron and hole), and therefore an increase in exciton-absorption peak. Furthermore, the increase in exciton mass and the change in the sign of the hole mass lead to reduced saturation effect -- an increase in saturation intensity. The major saturation mechanism is due to the band-filling effect (Pauli-exclusion effect). The saturation intensity is inversely proportional to the exciton lifetime because the shorter the lifetime the faster an optically created exciton disappears from the filled state. Changing the in-plane valence band structure can reduce the exciton lifetime by several orders of magnitude, thereby allowing higher intensities of light to be absorbed. With the effects of strain in MQW's, opto-electronic devices can be designed to achieve larger exciton-absorption and higher saturation intensity than currently available.

Normal incidence infrared photoabsorption in p-type GaSb/GaAlSb quantum wells

We have investigated infrared absorption properties at normal incidence in p-type GaSb/$Ga_{1-x}Al_xSb$ quantum wells. Normal incidence absorption is intrinsically allowed in conventional p-type quantum wells due to the favorable properties of the p-like valence-band Bloch states and the light-hole and heavy-hole mixing. Unlike s-like conduction-band Bloch states (|s>) for electrons, the Bloch states for holes are linear combinations of p-like valence-band Bloch states (|x>, |y>, and |z>), which can provide nonzero coupling to normally incident radiation. The strong heavy-hole and light-hole mixing due to the QW potential further promotes absorption at normal incidence. An advantage of this detection scheme is that it allows the use of wide- and direct-gap semiconductors. However, the inter-valence subband absorption in conventional p-type quantum wells, such as in p-type GaAs/$Ga_{1-x}Al_xAs$, is too small to be useful for photodetection applications. This is because in conventional p-type quantum wells free holes occur primarily in the heavy-hole ground state with large effective masses. Therefore weak absorption results from the inverse relationship between the effective mass of free carriers and the absorption coefficient. Taking into account the fact that smaller effective mass corresponds to stronger absorption, we choose a well material with a relatively small heavy-hole effective mass, GaSb, in order to strengthen the absorption. Among the widely used III-V semiconductors, GaSb has the smallest heavy-hole effective mass (m^*_{hh}/m_0 = *0.26*, m_0 is the free electron mass), which is about half the heavy-hole mass of GaAs ($m^*_{hh}/m_0 = 0.45$). Previously, we have taken advantage of this feature and fabricated p-channel GaSb field-effect transistors which exhibited the highest transconductance reported for any III-V compound p-channel field-effect transistors. Here, we found that normal incidence absorption of $3000\text{-}6000\ cm^{-1}$ can be easily achieved in these proposed quantum wells with well widths of *55-90 Å* for the wavelength range of $8\text{-}12\ \mu m$ and typical sheet doping concentrations of $10^{12}\ cm^{-2}$. This absorption strength is an order of magnitude larger than that in p-type GaAs/$Ga_{1-x}Al_xAs$ and comparable to that in the intrinsic $Hg_{1-x}Cd_xTe$ detector. Strong absorption of normally incident radiation makes this structure a good candidate for infrared photodetection.

Infrared absorption enhancement in light-hole and heavy-hole inverted strained GaInAs/AlInAs quantum wells

We have studied an alternative approach to improve the inter-valence subband absorption in p-type quantum wells. Absorption at normal incidence is found to be significantly enhanced in $Ga_{1-x}In_xAs/Al_{1-y}In_yAs$ quantum wells with light-hole and heavy-hole inversion. The inversion can be achieved with the effects of biaxial tensile strain in the quantum well due to the lattice mismatch between the well material and substrate. In this way p-type quantum well infrared detectors can be designed such that the light-hole state becomes the ground state for free holes with small effective masses, thereby producing stronger absorption. We found that in this light-hole and heavy-hole inverted structure with a well width of 60 Å, the infrared absorption can be greatly enhanced up to $8500\ cm^{-1}$ for normally incident radiation of $12\ \mu m$, which is comparable to that in the intrinsic $Hg_{1-x}Cd_xTe$ detector. This novel structure's ability to detect normally incident radiation makes it promising for infrared photodetection applications.

Normal incidence infrared absorption in AlAs/AlGaAs X-valley multiquantum wells

We have reported the first observation of normal incidence infrared absorption due to inter-conduction subband transitions in AlAs/AlGaAs X-valley multiquantum wells. Infrared absorption measurements were performed on samples grown on [111], [113], [115], and [001] substrates with normal incidence radiation at wavelengths of *5-20* μm. Two absorption peaks were observed in [113] and [115] multiquantum wells with well widths of *40 Å* and sheet doping concentrations of $10^{12}\ cm^{-2}$. One peak, due to transitions between the ground state and the continuum band occured at $7.1\ \mu m$; a second peak originating from inter-conduction subband transitions between the ground state and the first excited state occured at $17 \mu m$. The experimental results indicate the potential of these novel structures for use as normal incidence infrared photodetectors.

We have also investigated the dependence of normal incidence absorption from inter-conduction subband transitions on the growth direction in ellipsoidal-valley quantum wells. Due to the effective-mass anisotropy of electrons in the ellipsoidal valleys, normal incidence absorption is allowed in these structures when the growth direction is not collinear with the principal axes of the ellipsoidal valley which has the lowest first-state energy. We found that in the AlAs X-valley system the absorption is near optimal for such low-index orientated structures as [210] and [113] quantum wells.

AlGaAs-GaAs-InGaAs strained laser structure with performance insensitive to AlGaAs layer quality

It has been established from deep level transient spectroscopy (DLTS) and SIMS experiments that AlGaAs grown by MBE (and possibly MOCVD as well) always contains defects and impurities due to the incorporation of oxygen during crystal growth. These defects form traps in the AlGaAs wide-bandgap regions which serve as sources of non-radiative recombination that increase laser threshold and reduce the reliability of the device. The density of these defects can be minimized by performing AlGaAs MBE growth around 700 °C, however at this high growth temperature precise control of the GaAs thickness and Al composition is difficult to achieve due to the re-evaporation of Ga from the growing surface. We have studied and demonstrated a step separate confinement strained single quantum well laser that exhibits state-of-the-art threshold current densities which are insensitive to AlGaAs layer quality. The insensitivity of the threshold current density to AlGaAs quality is attributed to the use of a large GaAs region (~120 nm) outside the InGaAs quantum well. This large GaAs region reduces the influence of traps in the AlGaAs layer on the active region of the device. Laser structures with AlGaAs layers grown at different substrate temperatures (580 °C to 700 °C) exhibit similar threshold current densities while photoluminescence measurements on the AlGaAs layers of these samples exhibit large variations in the peak intensity. Thus large variations in the quality of the AlGaAs layers in our structure have little effect on the active region of the device. Our strained layer laser structure is useful for consistently producing low threshold lasers for experimental purposes and potentially offers improved reliability and manufacturability over GRIN-SCH structures due to the removal of non-radiative and dark line defect producing sites from the active region of the device. Conceivably, our structure can also be applied to other strained-structures with Al-containing compounds, such as InAlAs/In$_x$Ga$_{1-x}$As/In$_y$Ga$_{1-y}$As ($y<x$) and InAlP/In$_x$Ga$_{1-x}$P/In$_y$Ga$_{1-y}$P ($y<x$).

At present, a single InGaAs strained quantum well sandwiched between graded AlGaAs cladding layers, i.e. GRIN-SCH structure (graded-index separate confinement heterostructure), is the most commonly used strained laser structure. Although it has better carrier confinement than our structure, it is a difficult task to routinely produce the precisely graded and low defect density AlGaAs layers necessary for these GRIN-SCH structures.

P-Channel GaSb MODFET for Complementary Circuit Applications

We reported the successful operation of the first AlSbAs/GaSb p-channel MODFET. The AlSbAs/GaSb MODFET offers several advantages over AlGaAs/GaAs and strained layer InGaAs p-channel HFET structures. The hole mobility of GaSb of 850 cm^2/Vs at 300K is one of the highest in III-V compounds and is more than twice that of GaAs. In addition, a substantial valence band offset exists between AlSb and GaSb resulting in reduced gate leakage currents. For $1 \mu m$ gate length devices, transconductances of 50 mS/mm at room temperature and as high as 283 mS/mm at 77K were measured. This is the highest transconductance achieved for any p-channel compound FET with comparable geometry. We attribute this excellent performance to the superior transport properties of holes in GaSb. The devices exhibited gate leakage currents, measured at 77K, three orders of magnitude lower than the maximum drain saturation current. This low leakage current is due to the large valence band offsets in this material system. Thus an optimized p-channel device could be integrated with an AlSb/InAs n-channel HFET to lead to high performance complementary circuits.

As aforementioned, such p-channel devices can be integrated with our previously reported AlGaSb/InAs n-channel HFET to form a complementary circuit technology that is predicted to have a significant performance advantage over AlGaAs/GaAs C-HFET structures. The superior transport properties of electrons in InAs and holes in GaSb and their corresponding band offsets to AlSb or AlSbAs yield devices with transconductances much higher than AlGaAs/GaAs n- and p-channel HFETs. Consequently, we showed that a complementary circuit fabricated from these devices could provide room temperature performance with an ultimate gate delay six times shorter than that predicted for the AlGaAs/GaAs complementary circuits.

PAPERS PUBLISHED IN REFEREED JOURNALS

1. L.F. Luo, K.F. Longenbach, and W.I. Wang, "Kink-free AlInAs/GaInAs/InP HEMTs grown by molecular beam epitaxy", Electronics Lett. 26, 779-780 (1990).

2. W. Hansen, T. P. Smith, III, J. Piao, R. Beresford, and W. I. Wang, "Symmetry and strain effects in GaSb/AlSb quantum wells," Appl. Phys. Lett. 56, 81 (1990).

3. K.F. Longenbach, R. Beresford, and W.I. Wang, "Applications of dual-gate and split-gate field-effect transistor designs to InAs field-effect transistors", Solid State Electronics, 33, 1211-1233 (1990).

4. B.V. Shanabrook, D. Gammon, R. Beresford, W.I. Wang, R.P. Leavitt, and D.A. Broido, "Modification of the piezoelectric field in quantum wells", Proc. of the 20th International Conf. Physics of Semiconductors, p. 901-904, World Scientific, 1990.

5. B.V. Shanabrook, D. Gammon, R. Beresford, W.I. Wang, R.P. Leavitt, and D.A. Broido, "Modification of the piezoelectric field in quantum wells", Superlattices and Microstructures, 7, 363 (1990).

6. S. Tiwari, W.I. Wang, and J. East, "An analytic theory of the Auger transistor: a hot electron bipolar transistor", IEEE Trans. Electron. Dev. 37, 1121-1131 (1990).

7. K.F. Longenbach, R. Beresford, and W.I. Wang, "A complementary heterostructure field-effect transistor technology based on InAs/AlSb/GaSb", IEEE Trans. Electron Dev. 37, 2265-2267 (1990).

8. L.F. Luo, K.F. Longenbach, and W.I. Wang, "High performance GaSb p-channel MODFETs", International Electron Dev. Meeting, IEDM technical digest pp. 515-518 (1990).

9. Y. Jiang, M.C. Teich, and W.I. Wang, "The Auger recombination rate is larger in a GaSb quantum well than in bulk GaSb", J. Appl. Phys. 69, 836-840 (1991).

10. S. Xin, K.F. Longenbach, and W.I. Wang, " AlGaAs/GaAs/InGaAs strained layer laser structure with performance independent of AlGaAs layer quality", Electronics Lett. 27, 199-201 (1991).

11. L.F. Luo, K.F. Longenbach, and W.I. Wang, " P-channel modulation-doped GaSb field effect transistors", Electronics Lett. 27, 472-474 (1991).

12. Y. Jiang, M.C. Teich, and W.I. Wang, "Forbidden Auger process in strained InGaSb/AlGaSb quantum wells", Appl. Phys. Lett. 57, 2922-2924 (1990).

13. Q. Wang, Y. Wang, K.F. Longenbach, E.S. Yang, and W.I. Wang, "A two-dimensional electron gas emitter AlGaAs/GaAs heterojunction bipolar transistor" Appl. Phys. Lett. 59, 2582-2584 (1991).

14. Y. Wang, Q. Wang, K.F. Longenbach, E.S. Yang, and W.I. Wang, "A two-dimensional electron gas emitter AlGaAs/GaAs heterojunction bipolar transistors

with low offset voltage", Proc. of the 18th International Symposium on GaAs and Related Compounds, pp. 311-315, Seattle, WA (1991).

15. L.F. Luo, K.F. Longenbach, and W.I. Wang, "p-channel modulation-doped field-effect transistors based on AlSbAs/GaAs", IEEE Trans. Electron Dev. 11, 567-569 (1990).

16. H. Xie, J. Piao, J. Katz, and W.I. Wang, "Intersubband absorption in GaAlSb/AlSb superlattices for infrared detection", J. Appl. Phys. 70, 8152-8156 (1991).

17. K.F. Longenbach, S. Xin, and W.I. Wang, "p-type doping of GaSb by Ge and Sn by molecular beam epitaxy", J. Appl. Phys. 69, 3393 (1991).

18. K.F. Longenbach, X. Li, Y. Wang, and W. I. Wang, "Polytype InAs/AlSb/GaSb for field effect transistor applications", Proc. IEEE/Cornell Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, p. 270-279, 1991.(Invited paper)

19. Y. Jiang, M.C. Teich, and W.I. Wang, "Enhanced exciton absorption and satuartion limit in strained InGaAs/InP quantum wells", J. Appl. Phys. 71, 769-772 (1992).

20. H. Xie, J. Katz, and W.I. Wang, "Infrared absorption enhancement in light-hole and heavy-hole inverted InGaAs/InAlAs quantum wells", Appl. Phys. Lett. 59, 3601-3603 (1991).

21. H. Xie, J. Katz, W.I. Wang, and Y.C. Chang, "Normal incidence infrared photoabsorption in p-type GaSb/GaAlSb quantum wells", *J. Appl. Phys.* 71, 2844-2847 (1992).

22. X. Li, K.F. Longenbach, and W.I. Wang, "Observation of piezoelectric field induced carriers in AlGaAs/InGaAs strained-layer heterostructures", Appl. Phys. Lett. 60, 1513-1516 (1992).

23. I.W. Tao and W.I. Wang, "Strained InGaAs quantum well lasers grown on (111)B GaAs", Electron. Lett. 28, 705-706 (1992).

24. I.W. Tao, C. Schwartz, and W.I. Wang, "Improvement of the threshold current of AlGaAs/GaAs single quantum well lasers by substrate tilting", J. Vac. Sci. Tech. B10, 838-840 (1992).

25. X. Li, K.F. Longenbach, Y. Wang, and W.I. Wang, "High breakdown voltage AlSbAs/InAs n-channel field effect transistors", IEEE Electron Dev. Lett. 192-194 (1992).Also, presented at the Workshop on Strained-Layered Materials and Devices, SUNY Buffalo, August 23, 1991.

26. J. Katz, Y. Zhang, and W.I. Wang, "Normal incidence infrared absorption from intersubband transitions in p-type GaInAs/AlInAs quantum wells", Electron. Lett. 28, 932-934 (1992).

27. G. Brozak, B.V. Shanabrook, D. Gammon, D.A. Broido, R. Beresford, and W.I. Wang, "Effects of nonparabolicity on collective intersubband excitations", Phys. Rev. B15, 45, 11399-11402 (1992).

28. G. Brozak, B.V. Shanabrook, D. Gammon, D.A. Broido, R. Beresford, and W.I. Wang, "Intersubband transitions in piezoelectric superlattices", Surface Science 267, 120-123 (1992).

29. G. Brozak, B.V. Shanabrook, D. Gammon, D.A. Broido, R. Beresford, and W.I. Wang, "Effects of nonparabolicity on intersubband spin and charge-density collective excitations", ICPS-21, Beijing, China. (1992).

30. J. Katz, Y. Zhang, and W.I. Wang, "Normal incidence infrared absorption in AlAs/AlGaAs x-valley multiquantum wells", Appl. Phys. Lett. 61, 1697-1699 (1992).

31. H. Xie, J. Katz, and W.I. Wang, "Orientation dependence of intersubband absorption in AlAs/AlGaAs x-valley superlattices", J. Appl. Phys. 72, 3681-3685 (1992).

32. H. Xie, J. Katz, and W.I. Wang, "Growth orientation dependence of normal incidence absorption in ellipsoidal-valley quantum wells", App. Phys. Lett. 61, 2694-2696 (1992).

PATENTS FILED

none

GRADUATE STUDENTS WORKING UNDER CONTRACT

GRADUATE RESEARCH ASSISTANTS

Kevin L.F. Luo

Jennifer Katz

Xiaoming Li

Kort F. Longenbach